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**Final report on:**

**MAPPING THE SPATIAL EXTENT OF GROUND DUST AND DEBRIS FROM  
THE COLLAPSE OF THE WORLD TRADE CENTER BUILDINGS**

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## **NOTICE**

This document is a Final report. It has been peer-reviewed and comments reconciled.

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## ABSTRACT

This report presents the results of an analysis into the geographical extent of the ground dust/debris field produced by the collapse of the buildings at the World Trade Center (WTC) on September 11, 2001. The study focused on an area within an approximate eight mile radius from the World Trade Center. The study period ranged from September 11, 2001 through September 13, 2001. This temporal limit is due to an approximate two inch precipitation event on the morning of September 14, 2001. Various remote sensing imaging sources (*aerial photographic and satellite image data*) and analytical techniques (*qualitative interpretive analysis and quantitative image processing analysis*) were utilized in this study.

Results include:

c      High-spatial-resolution aerial photographs from September 11, 2001 and September 13, 2001 show distinct primary and secondary deposition along roadways, parking lots and other ground areas in lower Manhattan that extend as far north as Canal Street on the September 13 photographs. In the small area of Brooklyn covered by the September 13 photographs, possible dust is observed on pier areas adjacent the East River and directly south-southeast of the WTC area. An excavated area and multiple mounds of material are also observed on the piers in the general vicinity of the possible dust. The area of coverage for the high-spatial-resolution aerial photographs was generally limited to the lower Manhattan area during the study period. This limitation prevented a determination of ground dust/debris boundaries over the wider

study area

C On one-meter IKONOS-1 satellite imagery from September 12, 2001 ground dust/debris was observed in lower Manhattan. However, the extreme oblique perspective provided by the image precluded a boundary determination for the lower Manhattan area. For those areas outside of lower Manhattan, ground dust/debris could not be ascertained.

C Multi-temporal Landsat 7 ETM+ multispectral images (September 12, 2001 and August 27, 2001) and EO-1 Hyperion satellite hyperspectral data were used to assess ground dust/debris over a wide geographic area.

A qualitative assessment of spatial patterns of high reflectance change, derived from Landsat 7 temporal image ratio data, provided three distinct spatial patterns. One generally coincided with the ground boundaries derived from September 11, 2001 aerial photographs in lower Manhattan, south of Chambers Street. A second was related to the WTC plume and a third was related to the eastern edges of shorelines (land/water interface). Lower reflectance change, although prevalent throughout the study area, showed no coherent spatial pattern for ground dust/debris.

The spatial patterns derived from spectral signature mapping of EO-1 Hyperion data also showed a spatial coincidence with the ground dust/debris boundaries derived from September 11, 2001 aerial photographs in lower Manhattan, south of Chambers Street. An additional pattern was noted along the west side of Manhattan proceeding from the WTC area in the south towards Central Park to the north.

The maps produced from the Landsat and Hyperion data do not assure the presence or absence of ground dust/debris for any given pixel, but rather illustrate spatial relationships from which ground dust/debris, per pixel, may be qualitatively assessed. The spatial resolution provided by these sensors (30 meters) was not sufficient for interpretive mapping of ground dust/debris boundaries, such as those delineated using the high resolution aerial photographs.

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## INTRODUCTION

This report presents the results of an analysis into the geographical extent of the ground dust/debris deposition produced by the collapse of the buildings at the World Trade Center (WTC) on September 11, 2001. Specifically, the United States Environmental Protection Agency (USEPA) Office of Research and Development (ORD) was tasked by the USEPA Region 2 Response and Recovery Operations Team to evaluate remote sensing data to determine the geographical *ground* distribution of the dust/debris produced by the collapse of the buildings at the WTC in New York City, New York. The purpose of this mapping effort was to provide geographical boundaries in support of USEPA Region 2 response and recovery operations (Final WTC Test and Clean Program Plan, 2005).

The analysis encompassed an approximate 256 square-mile area centered on the WTC site (Figure 1). Remote sensing data collected September 11, 2001 through September 13, 2001 were utilized to investigate the spatial extent of the ground dust/debris field. This temporal limit is due to an approximate two inch precipitation event on the morning of September 14, 2001 (Appendix B; NCDC, 2001) that altered the extent of the original ground dust/debris field.

Remote sensing data analyzed for this study included:

1) Scanned, natural color, oblique aerial photographs collected from hand-held cameras on *September 11, 2001* by New York Police Department (NYPD) photographers on board NYPD helicopters (NYPD, 2002).

2) Digital imagery collected from various satellite sensor platforms on *September 12, 2001* to include IKONOS-1, Landsat 7 ETM+ and EO-1 Hyperion.

Additionally, Landsat 7 ETM+ image data collected on August 27, 2001, were acquired as a change detection vehicle to provide a pre and post September 11, 2001 comparison of landscape condition.

3) Analog, black and white (B+W) panchromatic, vertical aerial photographs collected on *September 13, 2001* by Keystone Aerial Survey (KAS) using a standard 9" x 9" frame aerial mapping camera.

The aerial photographic coverages from September 11, 2001 and September 13, 2001 provided the means for high-resolution interpretive mapping but were limited to the general area of lower Manhattan. Satellite imagery from September 12, 2001 provided a means of wide-area coverage of the area of interest for this report. In particular, Landsat 7 was included to meet the specific request of analysis over the entire two-hundred and fifty-six (256) square miles.

For this study, the dust/debris extent was defined by those boundaries produced from the collapse of the WTC buildings and demarcated as light/dark boundaries on the ground. For example, as determined from the aerial photographs, boundaries were generally distinct along the road network due to the contrast between the dark-toned road surfaces and the light-toned dust/debris. The dust/debris covered the road surfaces to the point where road and cross-walk lines were obscured. On the opposite side of the boundary some faint dust may have been present but not in a sufficient quantity to obscure surface details such as road lines or cross-walks (Figure 2B). In

contrast, it proved difficult to distinguish dust/debris boundaries atop light-toned roofs due to a lack of tonal difference. Given the possibility of gradations of dust/debris deposition on the landscape, areas of light dust/debris deposition may not be detectable from the remote sensing data included in this report and therefore it is possible that dust/debris may extend beyond the boundaries as delineated in this report.

In contrast, boundaries could not be interpretively mapped from medium spatial resolution satellite data (Landsat 7, Hyperion). Mapping results from these raster data were derived from image processing algorithms based on 1) pixel reflectance change per multi-date Landsat images, and 2) mapping of Hyperion data to endmember spectra from lower Manhattan. While these maps may have an association with dust/debris, they do not assure the physical presence/absence of ground dust/debris for any given pixel.

The report addresses the spatial extent of ground dust/debris deposition as an aggregate (paper, pulverized concrete and wall board, larger building materials, etc.) and is concerned with material that would change the tonal quality and spectral signature of ground features in the area-of-interest. It does not analyze the chemical or molecular composition of the ground dust/debris. Further, the analysis assumes no spatial correlation between ground dust/debris boundaries, as mapped in this report, and the dispersal of dust/debris into those areas above ground level.

The U.S. Environmental Protection Agency (EPA), Office of Research and Development, Environmental Sciences Division, Landscape Ecology Branch, Environmental Photographic Interpretation Center (EPIC) in Reston, Virginia prepared

this report for the USEPA Region 2 Response and Recovery Operations Team, New York, New York. The Figures in this report are located in Appendix A. Sources for the aerial photographs and digital imagery, evaluated for this report, are listed in Table 1. SPOT-4 and NYWCAP imagery, collected on September 12, 2001, were reviewed for this report, however, they did not provide additional detail on ground dust/debris and therefore were not included in this analysis.

Note: the New York State Office for Technology (NYSOFT) began contract airborne overflight operations with the Keystone Aerial Survey overflight on September 13, 2001. No known airborne overflight collection operations occurred on September 14, 2001. Airborne operations for daily collection of 1-foot digital camera imagery as well as Light Detection and Ranging (LIDAR) data of the WTC began on September 15, 2001.

## **GENERAL**

This report was prepared using a standard methodology that included the following procedures:

- \$ data identification and acquisition,
- \$ imagery analysis and mapping, and
- \$ graphics and text preparation.

Data identification and acquisition included a search of government and commercial sources of imagery encompassing the study area. Publicly available airborne and satellite imagery collected over the WTC for the time period September 11, 2001 through September 30, 2001 were identified and data matching the temporal

period September 11, 2001 through September 13, 2001 were acquired. United States Geological Survey (USGS) topographic maps as well as a September 15, 2001 IKONOS-1 one-meter rectified image were acquired and used as reference data to provide geographic context for the mapping of the dust/debris boundaries.

Analysis and mapping techniques applied to the various data were unique to each imagery type and included, 1) monoscopic visual interpretation of digital images viewed within a GIS environment, 2) stereoscopic visual interpretation of analog diapositive photographs viewed on a backlit light table, and 3) digital image processing utilizing pixel reflectance values. The individual data, methods and results of the mapping of the ground dust/debris are specifically detailed in the **Analysis** section by date and separate data type.

The process of visual interpretive analysis involves the examination and comparison of numerous components of the remotely sensed data. These components include shadow, tone, color, texture, shape, size, pattern, and context of individual elements of a photograph. The image interpreter identifies objects, features, and "signatures" associated with specific environmental conditions or events. In a visual interpretive context, "signature" refers to a combination of components or characteristics that indicate a specific object, condition, or pattern of environmental relevance. The professional and academic training, image interpretation experience gained through repetitive observations of similar features or activities, deductive logic of the analysts as well as collateral information are important factors employed in interpretive analysis. When utilizing analog overlapping photographs, the analyst may utilize a stereoscope to view a three-dimensional representation of the study area, thus providing the ability to view the three dimensional relationships of landscape features.

Digital image processing is the computerized application of algorithms to digital imagery. The algorithms utilize the reflectance value and/or the spatial context of a pixel to automate the process of interpretation and classification. However, while the maps produced from these methods may have an association with dust/debris, there is no assurance that the results are specifically due to the physical presence of ground dust/debris. The ENVI (RSI, 2004) and ERDAS IMAGINE (Leica Geosystems, 2004) image processing software packages as well as the ArcView GIS (ESRI, 2004) software package were utilized for the processing and analysis of digital imagery used in this report.

Mapped boundaries are presented on transparent overlays, attached to the figures, and discussed in the associated text. All mapped boundaries are approximate and will be identified in the graphics and text according to the analyst's degree of confidence in the evidence. A qualitative distinction is made between certain, probable, and possible identifications. When the analyst believes the identification is unmistakable (certain), no qualifier is used. Probable is used when a limited number of discernible characteristics allow the analyst to be reasonably sure of a particular identification. Possible is used when only a few characteristics are discernible, and the analyst can only infer an identification.

The satellite images and the image mosaic produced from the September 13 aerial photographs were rectified, prior to acquisition for this report, to the Universal Transverse Mercator (UTM) projection, Zone 18N, NAD 83 datum, units=meters. When necessary for overlay analysis and reporting, un-rectified data were rectified to the above projection. Rectification was completed via an image-to-image registration technique utilizing previously rectified images for reference control points. The rectified images presented in this report have not been evaluated for national map accuracy standards (NMAS).

The image figures in this report have been reproduced from either the original digital data (as acquired for this report) or from digital scans of analog data produced ~~in-house~~ on a UMAX Mirage II digital scanner at a scan resolution of approximately 800 dots per inch (dpi). All figures in the report have been printed at 720dpi. Although the reproductions allow effective display of the imagery and interpretive annotations,

they may have lower resolution than the original imagery. Therefore, environmental features identified from the original data and described in the text may not be as clearly discernible on the prints in this report. The specific images included in this report were chosen based on providing the reader with the best possible spatial context regarding the *in situ* environmental conditions, however boundaries were analyzed and mapped from many more photographs/images than were illustrated in this report. See Table 1 for a listing of photographs and images used for this report.

Remote sensing and geospatial processing Quality Assurance Standard Operating Procedures (SOPs), as set forth in the Master Quality Assurance Project Plan (MQAPP) under Remote Sensing Support Services Contract (RSSSC) 68-D-00-267, were implemented for this report (Appendix C). Additionally, SOPs as set forth in the Image processing and GIS software documentation were implemented in the processing of the data. Due to the lack of ground truth data for the study area, a quantitative error assessment of the mapping results could not be provided. However, multiple remote sensing analysts have provided input into the analysis, results and review of this study.

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## Analysis

This section is listed by date with data, methods and results reported for each data type.

### **September 11, 2001**

#### NYPD Aerial Photographs

##### *DATA*

Data from September 11, 2001 were provided by USEPA Region 2 in two formats:

- 1) One-hundred and ninety-seven (197) digital aerial images in JPG compressed image format were provided by USEPA Region 2. These data were produced from hand-held photographic images collected by NYPD photographers onboard NYPD helicopters on September 11, 2001. Metadata, such as camera type, photograph time-tags, sequence of collection, photographic scale, photographers name and scan resolution of the digital images were not provided, therefore the specific parameters of these data cannot be conclusively determined. A relative temporal reference frame was established based on the time of the collapse of WTC buildings 2, 1 and 7 (approximately 9:50 am, 10:30 a.m. and 5:30 p.m. respectively on September 11, 2001; FEMA, 2002). The identification and condition of the WTC buildings, in the images, provided a general collection time sequence. The images were collected at both low and high oblique perspectives with the image foreground generally focused on lower Manhattan. This collection characteristic generally limited the interpretable portion of the imagery (and the

ground dust/debris boundary determination) to the lower Manhattan area. A spatial index of the NYPD JPG images was not produced for this study.

- 2) NYPD oblique aerial photographs reproduced in the publicly available book Above Hallowed Ground (NYPD, 2002). These photographs were also collected by NYPD photographers onboard NYPD helicopters, however, these data were not available to the USEPA as individual photographs or scanned images for this report. Therefore, photographs from the book that were deemed necessary for inclusion in this report were scanned at 800 dots per inch (dpi), converted to a Tagged Image File Format (TIFF) format and utilized as figures in this report. Despite the lack of attributable metadata, the NYPD photographs were the “best available@ aerial image data source collected on September 11, 2001. The image scale of the data is variable due to the non-consistent flying height of the platform(s) as well as the oblique nature of the photographs.

## METHODS

The ground dust/debris boundaries were mapped by employing the combined means of visual interpretive mapping techniques (Avery and Berlin, 2002; ASPRS, 1997) and digital mapping methods within a GIS. On the computer screen, a “dual-view@ mode was employed whereby the un-rectified aerial images were visually analyzed in one view to determine the general placement of the dust/debris boundaries while, in a second view,@heads-up@digital collection techniques were employed to map the dust/debris vector boundary using the rectified mosaic in Figure 3 as a base map.

Visible boundaries delineated from September 11, 2001 data were based

primarily on tonal variation (light/dark feature demarcation) along paved roadways and parking lots as well as change analysis of pre and post collapse images of WTC buildings 1 and 2 respectively.

## *RESULTS*

Figures 2A through 2E are centered on the intersection of West street and Warren street in lower Manhattan and present examples of clearly visible ground boundaries produced by the WTC building collapse clouds. The figures are presented here in order to clarify the definition of a dust/debris boundary and to illustrate how the analysis and mapping proceeded in this report. Boundaries were generally distinct along the road network due to the contrast between the dark-toned paved road surfaces and the light-toned dust/debris. The dust/debris covered the road surfaces to the point where road and cross-walk lines were obscured. On the opposite side of the boundary some faint dust may have been present but not in a sufficient quantity to obscure surface details such as road lines or cross-walks (Figure 2B). It proved difficult to distinguish the dust/debris boundaries from light-toned rooftops due to a lack of tonal difference. As stated in the introduction, boundaries derived from visual interpretive analysis were based on clearly demarcated areas of contrast. Further, a distinction was observed with respect to the ground dust/debris directly deposited by the collapse clouds (WTC buildings 1 and 2 as shown on Figure 2A-2E) and secondary ground dust/debris deposition that may have been due to post-collapse dispersal vectors such as transportation and wind. This secondary condition is evident in Figure 3, along West Street, where vehicular traffic has likely redistributed dust north of the original boundary

(Stuyvesant School Bridge, Figure 2E).

Figure 3 is a rectified mosaic of the photograph displayed on pages 48 and 49 in Above Hallowed Ground (NYPD, 2002). The photograph was collected at a low-oblique perspective and provided a base map from which to present the boundary in lower Manhattan on a single image. The ground dust/debris boundary was derived from the analysis of multiple images, most of which were not presented in this report, and reflected ground dust/debris boundary conditions between 10:30 am (post-collapse, WTC buildings 1 and 2) and 5:30 pm (pre-collapse, WTC building 7) on September 11, 2001. The mosaic seam, observed in the center of Figure 3, is due to a lack of overlap between the scanned images (pp. 48-49 in Above Hallowed Ground) and the oblique characteristic of the aerial photograph.

No visible ground dust/debris boundaries could be determined for the limited areas of Brooklyn, adjacent the East River, where coverage was available.

Results (Figure 3) show the **northern** limit (between North End Avenue and Centre Street) of the ground dust/debris boundary at approximately Chambers Street. However, variations in the northern boundary are observed 1) between Reade and Duane streets along Greenwich Street, Hudson Street and West Broadway, and 2) between Duane and Thomas Streets along Church Street. To the **northeast**, the boundary appears to extend to the east from the vicinity of City Hall along a line approximately parallel and south of the Brooklyn Bridge (Frankfort Street) as it meets the Franklin Delano Roosevelt expressway (FDR). The **southern** boundary of the ground debris field appears to extend to Battery Park and to the surrounding southern

limits of Manhattan. The **western** boundary generally extends to the Hudson River.

The mapping of the **eastern** and **southeastern** boundaries (south of the Brooklyn Bridge and east of Pearl and Water Streets) was problematic due to the limited coverage of the area provided by the September 11, 2001 aerial photographs and the plume emanating from "Ground Zero@which obscured the area. However, a dust/debris boundary was delineated, for this day, based on the analysis of September 13, 2001 aerial photographs, where a "blanket@of ground dust/debris deposition - characterized by light toned dust that completely covered the roadways and obscured white road and cross-walk lines - was observed in the eastern and southeastern portions of lower Manhattan. The deposition characteristics in this area were consistent with areas of lower Manhattan that were impacted by primary deposition from the WTC building collapses on September 11, 2001. Therefore, it is likely that the boundary, south of the Brooklyn Bridge did extend up to the FDR and possibly to the raised FDR roadway as well as the adjacent piers along the East River on September 11, 2001. However, because of the limited coverage, no qualitative distinction of the ground dust/debris in this area was attempted on this date. See the results for September 13, 2001 for a more comprehensive assessment of ground dust/debris in this area.

**September 12, 2001**

Landsat 7 ETM+

*DATA*

Landsat 7 ETM+ satellite data (path14/row 32) of September 12, 2001 included six bands of multi-spectral data (bands 1-5, 7) ranging from the visible to mid-infrared at 28.5-meter spatial resolution and one band of panchromatic B+W data (band 8) at 14.5-meter spatial resolution (USGS, 2004a). Additionally a spatially coincident Landsat 7 ETM+ image from August, 27, 2001 was acquired and the identical bands were processed for analysis. These pre and post WTC building collapse datasets were processed in order to determine patterns of reflectance change that would be consistent with the deposition of ground dust/debris. These data also provided the best means for analyzing ground dust/debris across the entire 256 mile<sup>2</sup> study area (Figure 4, Figure 5).

## METHODS

ENVI software was used to process the Landsat 7 ETM+ data. Steps involved in the data processing chain for each date of data consisted of:

- 1) A geometric and radiometric correction to Level 1G was applied, prior to acquisition by the USEPA, by the source vendor EROS Data Center (USGS, 2004b).
- 2) A top-of-atmosphere correction (TOA) was applied to transform the pixel digital numbers (DN) to exoatmospheric reflectance values (Lillesand et al., 2004) and to provide a scene-to-scene reflectance calibration.
- 3) A 256 mile<sup>2</sup> subset centered on the World Trade Center site was clipped from the original scenes.
- 4) A Neighborhood Analysis consisting of a 3 x 3 pixel, mean spatial filter (Lillesand et al., 2004) was applied to each pixel to compensate for an approximate one pixel registration offset between the two dates of imagery. A low-pass, 3x3 mean filter

was used in order to maximize large-area patterns in brightness and to aid in the mapping of large area contiguous boundaries associated with the dispersal of the ground dust/debris. All subsequent analysis was performed using the spatially filtered pixel reflectance values.

5) Temporal image ratio change detection methods (Lillesand et al., 2004) were implemented as a means for identifying those pixels that increased in reflectance between the two dates of imagery. Temporal image ratioing is a digital *pre-classification* change detection technique that compares coincident, per band pixel reflectance values of the two rectified images (Jensen, 1996). In this study, the temporal image ratio approach compared the after image (September 12,  $T_2$ ) with the before image (August 27,  $T_1$ ) to compute a per-pixel reflectance change ratio ( $T_2 / T_1$ ). Ratio values  $> 1$  represented positive reflectance change over time.

The temporal image ratio algorithm was applied to each individual band to create seven separate change images. Although image ratio data for all bands were produced and analyzed, for purposes of graphic reporting, only image ratio data from band 7 and band 8 were illustrated for this report. Band 7 was the only band to approach an increase in mean reflectance change between the two dates (0.98, Table 1), and its spectral wavelength range (2.09 - 2.35 microns) was shown to have a strong relationship with the WTC dust material (Clarke et al., 2001). Band 8 was included due to the increase in spatial resolution (14.5 meters) which provided additional spatial detail. Pixel values corresponding to no-change and decreases in reflectance were not reported. While image ratio figures for bands 1-5 were not included here, their spatial

results were similar to the patterns observed in bands 7-8 and discussed below.

## RESULTS

The temporal image ratio results provided insight into the spatial pattern of change over the whole study area and allowed general conclusions based on those patterns. The ratio data do **not** assure the presence or absence of ground dust/debris, for any given pixel, but rather denote those pixels that have greatly increased in reflectance and thus may have an association with dust/debris deposition.

Figure 5 and Figure 6, based on results from band 8 and band 7, respectively, utilized pixel values corresponding to a positive increase in image ratio data of  $> 2$  standard deviations (SD). Data resident within this threshold ( $> 2$  SD) represented approximately 3% and 2% of the image ratio data in band 7 and 8 respectively and were utilized to detect those areas most related to increases in reflectance. From Figures 5 and 6 the following spatial patterns were observed:

1) The area of lower Manhattan, bounded approximately by Chambers street to the north, has substantially increased in reflectance between the two dates (Table 1). The boundary is in general spatial agreement with the ground dust/debris boundary mapped from the September 11, 2001 photographs (in orange on overlays). Table 1 is a summary of image ratio statistics derived for bands 1-5, 7 and 8 and provides the mean and SD for each band over the entire study area as well as a mean value, per band, for the area of lower Manhattan encompassed by the September 11 dust/debris boundary as determined from the NYPD photographs. Noted are the approximate 50% increases in the mean ratio values in lower Manhattan as compared to the mean values

for the entire study area.

**Table 1.** Summary statistics, per band, for Image Ratio brightness change values derived from multi-date Landsat 7 ETM+ imagery.

\* total area-of-interest = 256 miles<sup>2</sup> centered on the WTC.

\*\* 9/11 boundary as mapped from NYPD photos.

Landsat 7 ETM+: Band Number	Mean image ratio value for total area-of-interest *	St. Dev. of image ratio value for total area-of- interest	Mean image ratio value for area encompassed within the 9/11 boundary (Lower Manhattan) **
Band 1	0.73	0.13	1.01
Band 2	0.75	0.17	1.14
Band 3	0.76	0.21	1.27
Band 4	0.87	0.26	1.33
Band 5	0.9	0.32	1.39
Band 7	0.98	0.33	1.54
Band 8	0.81	0.23	1.28

2) high reflectance change is noted along the eastern shorelines of land/water interfaces throughout the study area. This pattern is possibly related to an east/west directional mis-registration of the two images which would have a particular effect of distorting reflectance ratios related to north/south trending linear features.

3) a large area of increased reflectance is associated with the plume extending from the WTC area to the southwest. The increase is probably due to reflectance from the plume and not necessarily associated with a change in ground reflectance due to deposition of dust/debris.

4) clouds and shadow, present on August 27 (Figure 4), dominate the northern

portions of the study area as well as portions of Queens, Brooklyn and New Jersey and were a source of large reflectance change. The reflectance areas related to the clouds and shadows, in proximity to lower Manhattan and the WTC plume, are mapped on Figure 5 and Figure 6 overlays. Due to the presence of clouds/shadows on August 27, no determination of ground reflectance change could be ascertained in these areas on September 12.

#### EO-1 Hyperion

#### *DATA*

The hyperspectral dataset from the EO-1 Hyperion sensor (USGS, 2004c) consists of 220 separate spectral bands covering the wavelengths from 0.4 -2.5 microns at a spatial-resolution of 30 meters. The Hyperion data covered an approximate 4.7 mile swath across the center of the study area (Figure 7).

#### *METHODS*

ENVI software was used to process the Hyperion data. Steps involved in the data processing chain consisted of:

- 1) removing noisy and defective spectral bands, by inspection, which reduced the dataset to 154 bands.
- 2) correcting for atmospheric effects by radiative transfer modeling using the software ACORN (Atmospheric CORrection Now; AIG, 2004).
- 3) noise reduction using principle component analysis (PCA).
- 4) identifying candidate regions in the data that contained materials of interest (in this case, ground dust/debris from the WTC collapse). Ground based spectral

signatures obtained by the USGS (Clark et al., 2001) were used to create a library of signatures (endmember spectra) for material identification and mapping purposes. This library was compared to spectral signatures in the Hyperion dataset and areas (pixels) matching entries in the library were used in the mapping algorithms. Spectral signatures were obtained just north of the WTC site and were used in the material mapping algorithms.

5) Areas matching these endmember spectra were mapped throughout the entire image. The Mixture Tuned Matched Filter (MTMF; Boardman, 1998) was used for this analysis due to the fact that the spectra of materials in cluttered urban areas are a mixture of many other materials at the pixel resolution of the Hyperion sensor (30 meters) . The spectral features of the WTC dust were similar enough to common building material found in urban areas to defeat the spectral feature algorithms. This problem, combined with the noise inherent in data obtained from space, made it difficult to spectrally differentiate ground dust/debris from the surrounding urban background material.

## *RESULTS*

As with the Landsat 7 reflectance change results, we found a spatial coincidence between the Hyperion results and the results derived from the September 11, 2001 aerial photographs in lower Manhattan south of Chambers Street (Figure 7, Figure 8). An additional pattern was noted along the west side of Manhattan proceeding from the WTC area in the south towards Central Park to the north.

The mapped areas do not assure the presence or absence of ground dust/debris

for any given pixel, but rather indicate the likelihood that a Hyperion pixel is spectrally similar in the signature library - here, ground dust/debris from the WTC building collapses in lower Manhattan.

### IKONOS-1

#### *DATA*

Rectified digital imagery data were collected by Space Imaging's IKONOS-1 satellite (Space Imaging Inc., 2004) at nominal four-meter multispectral spatial resolution and nominal one-meter panchromatic spatial resolution. These data were subsequently merged to produce a multi-spectral dataset at nominal one-meter resolution. The imagery covered approximately 50% of the study area (Figure 9 ) and included portions of Manhattan, Brooklyn, Staten Island and New Jersey. However, the low collection angle of acquisition of the sensor (approximately 32 degrees) produced a low-oblique image, rather than the standard near-vertical image, and served to degrade the spatial resolution and spectral integrity of the data. In the lower Manhattan area this caused extreme building layover/shadow on the imagery and obstructed ground/roadway visibility.

#### *METHODS*

The imagery was analyzed, using visual interpretive methods, from within the ArcView GIS environment.

#### *RESULTS*

Although a boundary map was not produced from the IKONOS-1 data, some areas of dust/debris were visible in lower Manhattan. Probable light-toned dust/debris

was visible along West Street extending north from the WTC area to approximately Canal street. Additionally, ground dust/debris was visible at discrete points (Figure 10) south of Canal Street along Church Street, along West Broadway, east of Centre Street in the vicinity of the approaches to the Brooklyn Bridge and in a parking lot located between Pearl and Water Streets to the south of the Brooklyn Bridge.

The distinctive light-toned demarcation of dust/debris, evident in lower Manhattan, was not observed in areas outside of lower Manhattan.

### **September 13, 2001**

#### KAS Vertical Aerial Photographs

#### *DATA*

Data from September 13, 2001 consisted of 78 B+W film diapositives (transparencies) of 9" x 9" vertical and oblique aerial photographs of the lower Manhattan collected at a scale of 1:6,000 (KAS, 2004). Time of collection was approximately 9:00a.m. eastern daylight time (edt). The areal coverage of the photographs (Figure 11) was limited to lower Manhattan and a small portion of Brooklyn west of Hicks Street and adjacent the East River.

#### *METHODS*

Visual stereoscopic interpretive techniques were employed using a Richards 500 zoom stereoscope backlit light table to determine the dust/debris boundaries. Stereoscopic viewing provided the ability to visualize vertical as well as horizontal spatial relationships of landscape features. As with the September 11, 2001 data,

"heads-up" digital collection methods were implemented to map the boundaries.

Determination of boundaries generally relied upon the analysis of tonal and texture variation, along with stereoscopic visualization, to delineate clearly defined light/dark edges associated with light toned dust/debris on dark toned road pavements.

## *RESULTS*

A probable change in the northern ground dust/debris boundary, in lower Manhattan, occurred between September 11, 2001 and September 13, 2001. The probable northern boundary on September 13 extended approximately to Canal Street with other possible areas of dust extending beyond Canal Street (Figure 12). Multiple possibilities exist for the apparent change in the northern dust/debris boundary. First, WTC building 7 collapsed in the intervening time period which may have caused a wider distribution of dust than that delineated for the September 11, 2001 dust/debris map. Second, a transportation vector may have brought about a redistribution of dust. This scenario is most evident along West Street which was apparently an ingress/egress route for WTC operations. And third, an atmospheric vector due to a shift in wind direction to the north-northwest on September 13, 2001 (NCDC, 2003). The new lower Manhattan boundary area, existing between Chambers and Canal Streets, is the outer limit of an irregular and patchy distribution of dust/debris that appears to have accumulated along roadways and curbs in high traffic zones. Throughout this area, vehicle tracks are visible in the dust on the roads. This is particularly evident along Canal Street in proximity to a probable heavy equipment staging area (Figure 13).

A possible area of ground dust/debris is observed in the Brooklyn pier areas, adjacent the East River, directly east of Governors Island and south-southeast of the WTC (Figures 12, 14, 15). The dust appears to be limited to pier areas along the East River, west of Columbia Street, and south of Congress Street. The southeastern limits could not be determined due to a lack of photographic coverage south of Sedgewick Street. The dust appears to lightly coat the paved areas of the wharfs (light-toned lines are visible) and distinct vehicle track patterns are observed in the dust (Figures 14, 15). The vehicle track patterns, however, are not observed on the roadways in the surrounding area, such as Columbia Street or the Brooklyn-Queens Expressway. Additionally, an excavation area with adjacent crane and multiple mounds of material are observed in the general vicinity of the possible dust (Figure 15). A specific association between the observed dust, the excavation activity and the mounded material could not be ascertained.

In addition, due to improved photographic quality and coverage of the September 13 photographs in comparison the September 11, 2001 photographs, a qualitative distinction was made regarding the ground dust/debris in the southeastern portions of lower Manhattan along the FDR and areas east along the river. Possible and probable ground dust/debris was now noted along the *raised* portions of the FDR and on the piers extending into the East River (Figure 12). These areas were obscured on the September 11, 2001 NYPD photographs and no qualitative distinction of the ground dust/debris was attempted from the September 11, 2001 photographs.

A more comprehensive ground dust/debris mapping effort in Brooklyn could not be accomplished due to a lack of photographic coverage east of Hicks Street.

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**Table 2.** Listing of Digital Imagery and Aerial Photographs used for Analysis

Image Source	Associated Figures	Date of Acquisition	Original Scale/GSD	Data type as supplied to EPA
Landsat 7 ETM+	4	08-27-01	28.5m	MS Imagery
NYPD	2-3	09-11-01	Variable	Color Photographs
Landsat 7 ETM+	5-6	09-12-01	28.5m	MS Imagery
EO-1 Hyperion	7-8	09-12-01	30m	HS Imagery
IKONOS-1	9-10	09-12-01	1m/4m	MS Imagery
SPOT-4	*	09-12-01	20m	MS Imagery
NYWCAP	*	09-12-01	Variable	Color Imagery
KAS	11-15	09-13-01	1:6,000	B&W Photographs
IKONOS-1	**	09-15-01	1m/4m	MS Imagery

NYPD: New York Police Department

NYWCAP: New York Wing Civil Air Patrol

KAS: Keystone Aerial Survey

MS: Multi-spectral

HS: Hyper-spectral

GSD: Ground Sample Distance

\* The SPOT-4 and NYWCAP imagery, collected on September 12, 2001, were reviewed for this report, however, they did not provide additional detail on ground dust/debris and therefore were not included in this analysis.

\*\* The IKONOS-1 imagery, collected on September 15, 2001, was used only as base data for Aheads-up@mapping of the September 11, 2001 and September 13, 2001 photographs.

## APPENDIX B: Local Climatological Data, New York C. Park, NY (NYC), SEP/2001

DEPARTMENT OF COMMERCE  
UNITED STATES OF AMERICA  
**SEPTEMBER 2001**  
**LOCAL CLIMATOLOGICAL DATA**  
NOAA, National Climatic Data Center

**NEW YORK C.PARK, NY**

CENTRAL PARK OBSERVATORY (NYC)

Lat: 40° 47' N Long: 73° 58' W Elev (Ground): 158 Feet  
Time Zone: EASTERN WBAN: 94728 ISSN #:0198-3601

DATE	TEMPERATURE °F						DEG DAYS BASE 65°		WEATHER	SNOW//ICE ON GND (IN)		PRECIPITATION (INCHES)		PRESSURE INCHES OF HG		WIND		SPEED - MPH															
	MAXIMUM	MINIMUM	AVERAGE	DEF FROM NORMAL	AVERAGE DEW PT	AVERAGE WET BULB	HEATING	COOLING		0700 LST	1300 LST	2400 LST	2400 LST	DEPTH	WATER EQUIV	SNOW FALL	WATER EQUIV	AVERAGE STATION	AVERAGE SEA LEVEL	RESULTANT SPEED	RES DIR	AVERAGE SPEED	5- SEC SPEED	MAXIMUM DIR	2- MIN DIR	DATE							
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24										
01	81	64	73	1.1	49	58	0	8	RA BR	0.0	0.10	29.70	29.84	4.3	33	7.0	21	06	14	31	0												
02	75	58	67	1.1	49	57	0	8		0.0	0.00	29.94	30.08	3.0	10	6.3	21	07	16	37	0												
03	79	61	70	1.1	56	61	0	8		0.0	0.00	29.91	30.05	2.7	20	4.1	17	19	12	19	0												
04	78	66	72	1.0	56	64	0	7	RA BR	0.0	0.14	29.78	29.92	4.1	25	1.1	16	25	13	38	0												
05	77	64	71	0	53	60	0	6		0.0	0.00	29.92	30.06	3.3	06	1.5	15	06															
06	80	59	70	1.1	53	60	0	5		0.0	0.00	30.03	30.17	0.6	26	9.7	13	19	9	18	0												
07	85	65	75	1.4	44	60	0	10		0.0	0.00	29.95	30.09	4.6	23	5.9	18	25	13	26	0												
08	83	66	75	1.4	45	65	0	10		0.0	0.00	29.98	30.12	4.5	23	6.1	24	13	23	0													
09	83	69	76	1.4	46	66	0	11		0.0	0.00	30.03	30.17	4.9	20	1.9	14	17	14	27	0												
10	86*	68	77*	1.3	47	70	0	12	RA FG+ BR	0.0	1.16	29.95	30.08	4.2	21	6.4	23	26	16	27	1												
11	81	63	72	1.1	49	60	0	7		0.0	0.00	29.35	30.09	2.4	34	4.4	16	31	13	30	1												
12	79	60	70	1.1	52	59	0	5		0.0	0.00	30.02	30.16	0.6	27	5.7	17	25	12	24	1												
13	85	64	75	1.4	58	64	0	10		0.0	0.00	29.89	30.03	4.7	27	6.9	23	06	17	05	1												
14	68	53	61	1.1	53	54	4	0	RA FG BR	0.0	1.30	29.99	30.13	4.3	04	5.7	28	07	21	07	1												
15	68	53	61	1.1	44	52	4	0		0.0	0.00	30.01	30.16	3.8	03	5.7	21	07	16	07	1												
16	72	53	63	1.5	47	55	2	0		0.0	0.00	29.95	30.09	1.2	07	2.7	16	07	10	07	1												
17	77	56	67	1.1	51	58	0	0		0.0	0.00	29.92	30.07	0.7	27	3.5	12	26	9	06	1												
18	78	59	69	1.1	54	60	0	0		0.0	0.00	29.87	30.01	0.8	34	3.7	13	06	13	07	1												
19	78	61	70	1.1	59	63	0	0		0.0	0.00	29.98	30.12	1.6	13	1.6	20	18	14	17	1												
20	72	64	68	1.1	56	66	0	0	RA BR	0.0	0.83	29.94	30.08	5.4	19	6.1	28	23	16	23	0												
21	75	64	70	1.3	67	68	0	5	RA BR	0.0	0.36	29.85	29.99	2.9	20	4.3	22	21	14	23	0												
22	79	66	73	1.2	65	67	0	0	BR HZ	0.0	0.00	29.84	29.98	2.7	25	3.9	34	18	10	18	0												
23	78	63	71	1.5	61	64	0	6	BR	0.0	0.00	29.91	30.05	1.5	09	3.4	13	06	10	07	1												
24	75	67	71	0.6	68	69	0	6	RA BR HG	0.0	0.04	29.78	29.92	5.6	17	6.0	25	18	16	17	0												
25	72	57	65	0	63	64	0	0	RA BR	0.0	0.41	29.66	29.80	5.6	25	6.9	32	20	20	18	2												
26	64	50	57	1.8	43	50	8	0		0.0	0.00	29.81	29.95	5.8	27	6.8	21	28	15	28	2												
27	66	53	60	1.4	46	53	0	0		0.0	0.00	29.77	29.91	4.1	26	5.6	30	26	14	25	2												
28	67	50	59	1.5	47	52	0	0	RA	0.0	0	29.80	29.94	3.0	02	5.6	30	07	15	06	2												
29	64	53	59	1.5	45	52	0	0		0.0	0.00	29.95	30.10	10.8	06	11.3	32	05	22	07	2												
30	55	50*	53*	1.0	42	47	13	0	RA	0.0	0.36	29.94	30.08	11.5	06	11.7	32	05	22*	06	3												
		75.3		60.0		57.7		55.7		60.6		1.6		< MONTHLY AVERAGES		TOTALS		9.0		5.39		29.90		30.04		0.3		24.5		5.71		<-- MONTHLY AVERAGES	
		- .3		- 1		- .5		■■■		<-- DEPARTURE FROM NORMAL		>		1.41		SUNSHINE, CLOUD, & VISIBILITY TABLES ON PAGE 3																	
		DEGREE DAYS		MONTHLY TOTAL DEPARTURE		SEASON TO DATE TOTAL DEPARTURE		NUMBER OF DAYS WITH THUNDERSTORMS		MAXIMUM TEMP ≥ 90°		MINIMUM TEMP ≤ 32°		PRECIPITATION ≥ 0.01 INCH		SEA LEVEL PRESSURE		DATE		TIME													
		HEATING:		47		13		47		49		50		50		39.23		06		0853													
		COOLING:		137		7		1183		104		0		0		29.68		25		0251													

SEPTEMBER 2001  
NEW YORK C.PARK, NY

# HOURLY PRECIPITATION

(WATER EQUIVALENT IN INCHES)

## NEW YORK C.PARK, NY

SEPTEMBER 2001 NYC WBAN # 94728

DATE	FOR HOUR (LST) ENDING AT												DATE	FOR HOUR (LST) ENDING AT												DATE
	1	2	3	4	5	6	7	8	9	10	11	12		13	14	15	16	17	18	19	20	21	22	23	24	
01	0.10												01												01	0.10
02													02												02	0.00
03													03												03	0.00
04													04	0.08											04	0.14
05													05												05	0.00
06													06												06	0.00
07													07												07	0.00
08													08												08	0.00
09													09												09	0.00
10													10												10	1.16
11													11												11	0.00
12													12												12	0.00
13													13												13	0.00
14	0.38	0.05	0.30	0.13		0.16	0.19	0.35	0.20	0.06	0.02	0.03	14	0.02	0.01	T									14	1.90
15													15												15	0.00
16													16												16	0.00
17													17												17	0.00
18													18												18	0.00
19													19												19	0.00
20													20	0.16	0.03	0.07	0.12	T	T	0.24	0.02	0.01	0.06	0.01	20	0.83
21	0.03			0.16	0.17	T							21												21	0.36
22													22												22	0.00
23													23												23	0.00
24													24												24	0.04
25	0.11	0.12	0.07	0.03	0.04	0.01			0.01	0.01	0.01		25												25	0.41
26													26												26	0.00
27													27												27	0.00
28													28												28	T
29													29												29	0.00
30													30	T	0.03	0.01	0.03			0.11	0.04	0.10	0.03	0.01	T	0.36

### MAXIMUM SHORT DURATION PRECIPITATION (See Note)

Time Period (Minutes)	5	10	15	20	30	45	60	80	100	120	150	180
Precipitation (inches)	.26	.37	.41	.44	.57	.57	.57	.58	.58	.60	.73	.84
Ending Date	14	10	10	10	10	10	10	10	10	14	14	14
Ending Time (Hour/Min)	0029	1418	1421	1836	1843	1843	1843	1843	1843	0841	0252	0322

Date and time are not entered for TRACE amounts.

Note : The sum of the hourly totals is given when it differs from the daily total. NWS does not edit ASOS hourly values but may edit daily and monthly totals. Hourly, daily, and monthly totals are printed as reported by the ASOS site.

NOAA, National Climatic Data Center

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## APPENDIX C: Listing of Standard Operating Procedures.

The following remote sensing and geospatial Quality Assurance Standard Operating Procedures (SOPs), as set forth in the Master Quality Assurance Project Plan (MQAPP) under Remote Sensing Support Services Contract (RSSSC) 68-D-00-267, were implemented for this report.

<u>SOP Number</u>	<u>SOP Title</u>
1. RS-04-97-01-R11	Data Searches
2. RS-04-98-08-R4	Digital Imagery Acquisition
3. RS-05-98-08-R5	Maintaining Project Files
4. RS-06-97-07-R7	Inventory Control
5. RS-05-97-06-R9	Standard Category 3 Report Writing and Basic Measurements
6. RS-05-97-07-R9	Standard Category 3 Site Analysis Quality Control
7. RS-06-97-03-R7	Producing Category 3 Reports
8. RS-05-97-02-R9	Photointerpretation: Hazardous Waste Sites
9. RS-05-97-04-R6	Photointerpretation: Land Use/Land Cover
10. RS-05-98-11-R7	Production of Digitally Scanned Images
11. RS-08-98-09-R4	Geometric Rectification of Scanned Aerial Photos
12. RS-09-99-01-R2	Mosaicking of Digital Imagery
13. RS-08-98-08-R3	GIS Coverage Quality Control
14. RS-08-98-05-R5	GIS Metadata Documentation